AN OPERATIONAL CONCEPT FOR FLYING FMS TRAJECTORIES IN CENTER AND TRACON AIRSPACE

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ABSTRACT

Current Flight Management Systems (FMS) do a good job of constructing and flying an optimal trajectory for a single aircraft. Unfortunately, flight crews are often unable to fly these FMS routes during arrivals at busy airports. The Center TRACON Automation System (CTAS) has been designed to aid Center and TRACON controllers in assigning runways, sequencing and vectoring all classes of aircraft. CTAS bases its advisories on trajectory predictions for arriving aircraft using algorithms very similar to those in airborne FMS systems.

This paper presents near and far term operational concepts for how an ATM automation system like CTAS could work more effectively with the airborne automation in FMS equipped aircraft. The concepts for a more compatible air-ground system include: 1) common route databases for both CTAS and FMS; 2) datalink to downlink information on aircraft state, weight, final approach speed and trajectory intent and to uplink wind information; 3) new FMS functions to allow flight crews to easily update their FMS trajectory to match the trajectory suggested by the ground automation with voice clearances; and, 4) datalink to downlink user preferred trajectories and to uplink trajectory clearances.

This paper discusses some of the human factors issues that may result in allowing aircraft to fly FMS trajectories during en route descents and in the terminal area. A series of linked human-in-the-loop flight deck and air traffic control simulations are being conducted at NASA's Ames and Langley Research Centers to address these issues and to evaluate the operational feasibility of these approaches to more efficient flight and increased airport throughput.

INTRODUCTION

Following the Airline Deregulation Act of 1978, air travel has been experiencing an explosive growth which has placed heavy demands on the National Airspace System. Airspace users have cited insufficient system capacity, limited access, and operating restrictions as contributors to excessive operating costs and decreased efficiency. As a consequence, improvements are desired by system users in airspace system capacity, user flexibility, and efficiency. All these must be accomplished without compromising safety. NASA and the FAA have been developing the Center TRACON Automation System (CTAS) to address some of these issues.

The goals of the CTAS/FMS project of the Terminal Area Productivity program are to define requirements for airborne procedures and FMS functions that meet Air Traffic Management (ATM) requirements and for ground procedures and CTAS functions that permit more use of FMS procedures to improve terminal area productivity according to the following measures: 1) capacity or throughput - by reducing excess separation buffers in current operations; 2) flexibility - by allowing users to fly desired trajectories; and, 3) efficiency - by allowing maximal usage of flight management systems.

PROBLEM DEFINITION

Aircraft arriving today at busy terminal areas are controlled by highly skilled operators working with procedures and tools that are highly evolved for the task of safely controlling arrival traffic. The current mode of control is tactical and sector specific. Controllers work to meet speed, altitude and spacing requirements as the aircraft is passed to the next sector. From the pilot's trajectory point of view the resulting clearances may appear to be excessive and uncoordinated. Pilots complain of vectors off their preferred lateral routing, clearances to slow down followed by requests to speed up, and early descents to inefficient lower altitudes. These tactical clearances make it difficult to fly the efficient trajectory computed by their aircraft's FMS system.

In TRACON airspace, few FMS routes exist, and even when they do exist, aircraft can seldom remain on FMS routes during moderate to high traffic load because the controller can not control the aircraft without vectoring them off the FMS route. In the TRACON airspace, allowing aircraft to fly fixed lateral routes to the final approach does not allow controllers enough flexibility to control traffic. In today's system, aircraft must be given heading and speed vectors to merge them onto the final approach. This practice is safe and robust but measures of interarrival separation indicate that there is potential to increase runway throughput by more precise control (Ballin, 1996).

APPROACH

Benefits may be possible by taking a more strategic view. Longer term strategic planning can minimize the need for short term tactical control. But there are problems of attempting more strategic control. More planning is involved. Larger sections of a flight plan must be communicated between ground and air. The resulting system may be less flexible. If only FMS aircraft are capable of fully participating in a more strategic system then procedures have to be developed to deal with mixes of FMS and nonFMS equipped aircraft.

The CTAS/FMS project is developing air and ground systems and procedures that will allow FMS trajectories to be flown in Center and TRACON airspace. In Center airspace, these FMS trajectories should be closer to efficient "user-preferred" idle descent flight profiles. In TRACON airspace, these FMS trajectories should allow more precise control of inter-aircraft spacing and hence increases in runway throughput. A key challenge will be to develop procedures and decision support tools for air traffic controllers which allow them to give pilots fewer and more precise clearances that meet more strategic objectives while still remaining effectively "in the loop."

CTAS AND FMS CAPABILITIES

CTAS provides Decision Support Tools (DSTs) for both Center and TRACON controllers. CTAS bases its advisories on accurate predictions of the trajectories of arriving aircraft (Erzberger, 1993). The Traffic Manager Advisor (TMA) uses these trajectory predictions to calculate the expected, earliest and latest arrival time for each aircraft. The TMA produces an efficient sequence and schedule for when aircraft should arrive at meter fixes on the TRACON boundary. When the number of arriving aircraft exceeds the airport capacity the TMA schedule calculates the amount of delay each aircraft should absorb (Swenson, 1997).

The Descent Advisor (DA) is designed to help Center controllers plan a conflict free trajectory for each arriving aircraft that will result in it arriving at the TRACON meter fix at the TMA schedule time. Based on accurate aircraft performance models and estimates of the wind the DA provides advisories on the cruise and descent speeds that each aircraft should fly. If delays exceed those that can be absorbed with speed alone the DA assists the controller in issuing heading vectors or altitude changes to absorb the delay. The DA is designed to help the controller allow aircraft to make efficient idle thrust descents (Green, 1995 and 1996).

In TRACON airspace the Final Approach Spacing Tool (FAST) provides runway assignment and sequence advisories. FAST is being designed to provide turn, speed and altitude advisories to assist controllers in accurately vectoring aircraft onto the final approach along conflict free paths. These advisories are based on a route database that specifies how the lateral path and speed can be varied to deliver aircraft along conflict free trajectories precisely spaced at the final approach fix (Davis, 1994). The TMA is being evaluated at Dallas Ft. Worth Center and a "passive" version of FAST that provides advisories for runway assignment and landing sequence is being evaluated at the Dallas Ft. Worth TRACON (Denery, 1997).

The Flight Management Systems in current "glass" cockpit aircraft permit aircraft to accurately and efficiently fly a prespecified sequence of trajectory segments with speed and altitude crossing restrictions. At a mathematical level both CTAS and FMS systems are based on similar trajectory calculations but as currently implemented they are not operationally compatible. FMSs permit an aircraft to accurately and efficiently fly a preplanned trajectory. These work well when no additional constraints or lateral path changes are imposed by the air traffic management system. However, when new constraints must be imposed, current FMS systems require significant pilot input to allow them to meet these constraints. In some cases, the FMS is not functionally capable of incorporating constaints imposed by CTAS due to differences in the trajectory generation techniques. Pilots usually have to disconnect the lateral LNAV and vertical VNAV FMS functions and revert to more tactical autopilot modes.

Our approach to developing a more compatible air-ground system includes: 1) common route database for both CTAS and FMS (adapting CTAS to current FMS navigation standards); 2) datalink to downlink information on aircraft state, weight, final approach speed and trajectory intent and to uplink wind information; 3) new FMS functions to allow flight crews to easily update their FMS trajectory to match the trajectory suggested by the ground automation with voice clearances; 4) datalink to downlink user preferred trajectories and to uplink trajectory clearances; and, 5) human-computer interface design to help controllers plan efficient conflict free arrival trajectories.

OPERATIONAL CONCEPT

As an aircraft arrives in Center airspace, the TMA computes the scheduled time that the aircraft should arrive at the meter fix on the TRACON boundary. If the expected delay is less than a few minutes, the DA advises a cruise and descent speed that will deliver the aircraft to the meter fix at the TMA scheduled time. The flight crew enters these speeds into their FMS and flies the descent in LNAV and VNAV. Due to other traffic and high altitude/low altitude sector boundaries the initial clearance may be to an intermediate altitude, not the final meter fix altitude. If the expected delay is greater than can be achieved with speed control alone, the controller can vector the aircraft off the direct route to the meter fix, and the DA will advise when the aircraft should be turned back. If the aircraft is datalink equipped, a route modification with this turn back point could be uplinked to the aircraft as a route modification.

Field tests of the DA at Denver Air Traffic Control Center in 1994 and 1995 showed that these procedures can deliver aircraft to the meter fix at the scheduled time with a standard deviation of only 15 seconds

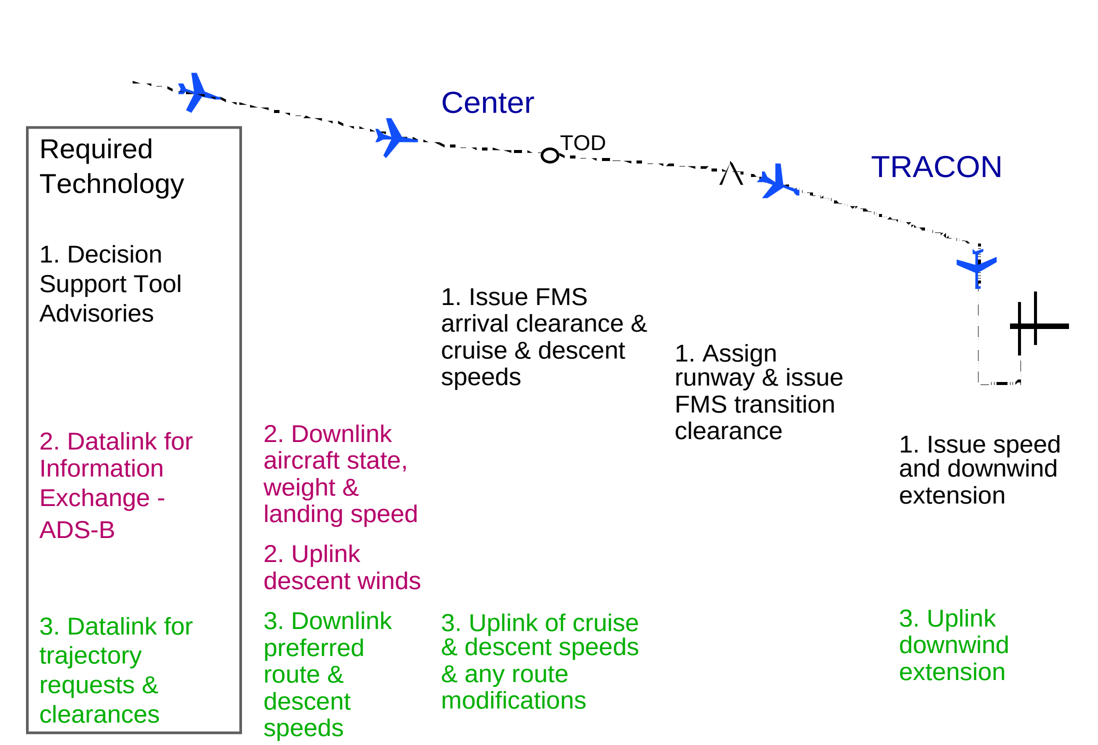

Figure 1. CTAS/FMS Scenario Events for different levels of technology.

(Green, 1995 and 1996, Williams, 1998).

As the aircraft arrives in TRACON airspace FAST advises a runway assignment. The aircraft is cleared on an FMS transition from the end of the FMS arrival to the downwind leg. The FMS route does not extend all the way to the final approach in order to allow the controller flexibility in when to turn aircraft to the base leg (Romahn, 1999). We will investigate three advisory options for when to make the turn from the downwind leg to the base leg; 1) no advisory will be provided, 2) FAST will provide a base turn advisory; and, 3) the controller will be able to uplink as an FMS route modification the lateral route advised by FAST from the downwind leg to the final approach fix. Speed advisories will also be displayed to the feeder controllers to help deliver a good flow of aircraft to the final controller. Typical scenario events for the CTAS/FMS concepts are shown in figure 1 for different levels of technology.

DATALINK FUNCTIONS

The use of datalink is what distinguishes our near and far term concepts. Our near term concept for CTAS/FMS compatibility does not require the use of datalink. Our far term concept includes the use of datalink to exchange information between air and ground and to uplink route modification clearances. It does not include the use of datalink for tactical clearances. Downlink of information such as aircraft state, weight and planned final approach speed allows CTAS to make better predictions of an individual aircraft's 4D trajectory. Uplink of winds to the aircraft's FMS system also helps align FMS and CTAS trajectory predictions. In Center airspace datalink equipped aircraft will also be able to downlink their preferred arrival trajectory. The controller will be able to check this route for conflicts and if it is conflict free, clear the aircraft to fly it. If additional constraints must be imposed, the Center controller will be able to uplink a route modification clearance which the flight crew can autoload into their FMS system. In TRACON airspace, our far-term concept also employs route modification clearances to uplink the FAST computed route from the downwind leg to the final approach fix.

In the far term, we assume that Automatic Dependent Surveillance - Broadcast (ADS-B) information on aircraft position, vertical velocity, track angle and estimated time of arrival at trajectory change points - such as, top-of-descent - is available to the ground. This improved information will allow CTAS to make better predictions of the aircraft's 4D trajectory. Perhaps as importantly, it will also improve the precision and timeliness of information on the controller's plan view display.

POTENTIAL BENEFITS

Shared information between air and ground automation will improve the accuracy of CTAS's trajectory and arrival time predictions. Better information and predictions will in turn result in more accurate and efficient control. The Descent Advisor will help the Center controller plan efficient descents with minimal restrictions to user-preferred FMS VNAV computed arrival trajectories. Aircraft on FMS trajectories in the TRACON that match FAST plans will be more predictable than vectored aircraft. Analysis and piloted flight simulations have shown that if an aircraft can remain on its LNAV trajectory until the final approach that the aircraft will arrive at the final approach fix within a few seconds of the time scheduled by FAST (Couluris, 1997 and Oseguera-Lohr, in preparation). More strategic clearance and the use of datalink for route modification clearances should also result in the need for fewer voice communications with the aircraft. (Romahn, 1999)

RESEARCH ISSUES

The strengths and weaknesses of this concept both result from moving from a tactical to a more strategic mode of control. Both pilot's and controller's tasks will require greater use of automation and decision support tools. Air and ground tasks will shift toward planning aircraft trajectories and compliance monitoring of plan execution. On the flight deck this implies using the FMS during descent and terminal area phases of flight during which it is often airline policy today not to use FMS LNAV and VNAV modes. Field and simulator studies have shown that pilots may need more training to effectively use FMS systems in these busy flight phases (Crane, 1997). In addition since the systems have not been as extensively used the guidance logic and control laws may require additional refinement to function properly in these more demanding phases of flight (Quarry, 1999).

On the ground the use of automated decision support tools will have a significant impact on how controllers perform their tasks. Tasks will shift toward longer term trajectory planning and compliance monitoring and away from shorter term tactical vectors. The trajectory planning will be aided by decision support tools which solve traffic problems with strategies that may be different than those that have been developed over many years by controllers to manually control traffic (Smith, 1999). For example, the Descent Advisor strategy for controlling arrival time is to compute the cruise and descent speed that will deliver the aircraft at the correct time at a meter fix. A controller's manual strategy is more local and likely to use a mix of heading vectors, speed changes and descents to lower altitudes to control arriving traffic.

Conflict probes will be available to automatically check an aircraft's planned trajectory against other aircraft trajectories but even if the "hockey pucks" defining the protected airspace around an aircraft do not intersect, a conflict free trajectory may not be one that is consistent with manual control strategies or one that can easily be monitored. For example, the DST approved trajectory may be conflict free but may not account for current positive separation procedural requirements.

New air and ground capabilities will be introduced gradually so controllers will have to cope with aircraft with a variety of FMS and datalink capabilities. This is an issue not only for controllers but for the automation software as well. FAST and DA will need to update the trajectories for aircraft depending on whether strategic or tactical clearances must be issued for specific aircraft.

More strategic clearances will require that clearances contain more information. Simulator and field tests of more strategic descent clearances have shown that the longer clearance resulted in more communication errors (Palmer, 1997 and Crane, 1997). Voice clearances will have to make more use of charted and database FMS procedures. Datalink may be the only promising approach for reliably transmitting trajectory clearances. Both controllers and pilots will have the new role of accessing and then monitoring clearances developed and executed by automation.

SIMULATION STUDIES

The CTAS/FMS project is conducting a series of linked human-in-the-loop flight deck and air traffic control simulations to explore the operational feasibility of these concepts.

A piloted simulation was conducted at NASA-Langley to document the trajectory errors associated with use of an airplane’s FMS in conjunction with CTAS in TRACON airspace. Integrating the trajectory prediction capabilities of the two automation systems in the terminal area could enable airplanes to fly accurate FMS trajectories that are matched by CTAS-predicted trajectories, resulting in better arrival-time predictions over current-day procedures. Three different arrival procedures into DFW airport were compared, beginning at the TRACON metering fix and ending at the outer marker. The three procedures used were current-day (vectors from ATC), modified (using current-day procedures with minor procedure updates), and datalink with FMS-coupled autopilot. All represent current or near-term capabilities, with the datalink procedure requiring the most changes to current-day operations. Seven active airline pilots were invited to fly the simulated arrivals in a fixed-base simulator, and provided subjective comments in addition to the simulation data collected. The FMS-datalink procedure resulted in the smallest time and path distance errors, indicating that use of this procedure could reduce the CTAS arrival-time prediction error by about half over the current-day procedure. The modified procedure did not result in a substantial improvement in arrival-time accuracy or path distance errors over current-day procedures, but had smaller cross-track errors. Significant sources of error contributing to the arrival-time error were cross-track errors , and early speed reduction in the last 2-4 miles before the outer marker. Pilot comments were all very positive, indicating the FMS-datalink procedure was easy to understand and use. There was some increase in head-down time and workload but the participating crews felt that this was acceptable. Significant issues remain to be resolved before this system is ready for operational use. These include development of procedures acceptable to controllers, changes to procedures to account for speed differences, and certification of database procedures to support the FMS approach transitions (Oseguera-Lohr, in preparation).

Another piloted simulation was conducted at NASA-Ames to investigate pilot performance and acceptance of FMS and CTAS/FMS procedures for the descent phase of flight. FMS procedures consist of charted and database lateral and vertical routings from late cruise up until final approach, and required crews to fly coupled in LNAV and VNAV FMS modes during descent. CTAS/FMS procedures required use of the

CDU interface to the FMS with the addition of new interface functions that allow the flight crew to update database FMS routes via datalink or manual crew input. Route updates were based on CTAS advisories that were assessed and communicated to crews by controllers. Twelve flight crews from two major airlines each flew seven descents in the Advanced Concepts Flight Simulator under current day, FMS, and CTAS/FMS procedure conditions. Results indicate that workload remained at or below acceptable levels in the FMS and CTAS/FMS conditions. Crews were less precise with speed control while flying in the VNAV descent mode during the FMS and CTAS/FMS procedures than in the current day procedures where the use of FLCH mode was common. In FLCH mode, the autopilot directly controls speed. However, in VNAV, the autopilot controls path and only provides alerts to the crew if the aircraft over speeds. Crews were able to successfully execute FMS route modifications received via voice or datalink in both the Center and TRACON airspace during FMS descent. Crew acceptability of the procedures and interfaces was generally high. However some pilots expressed reservations to the use of VNAV in the TRACON (Crane, 1999).

Two large scale proof-of-concept simulations involving the B757 simulator at NASA-Langley and Center and TRACON ATC simulations at NASA-Ames are being planned. The primary design variables will be the use or not of : 1) high quality ADS-B information on aircraft state and intended trajectory; 2) CTAS descent advisories in Center airspace and Speed and turn advisories in TRACON airspace; and, 3) the use of datalinked route modification clearances. Traffic density, traffic equipment mix and wind modeling errors will be varied for the different point designs.

CONCLUDING REMARKS

The CTAS/FMS operational concept has been designed to demonstrate a proof-of-concept system in which 1) information is exchanged to better coordinate air and ground trajectory and arrival time predictions, 2) aircraft can fly user preferred arrival and descent trajectories in transition airspace, and 3) aircraft fly FMS routes in the TRACON that match routes that FAST is recommending for more precise control of interarrival spacing. Human-in-the-loop simulations with prototype systems are underway to evaluate the operational feasibility of these concepts.

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